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An Accurate Velocity Estimation Algorithm for Resource Management in Next Generation Wireless Systems

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Abstract— **Information about a mobile user's velocity is important for efficient resource management and quality of service (QoS) provisioning in next generation (NG) wireless systems. A mobile receiver's velocity spreads the received signal envelope in the frequency domain. This spreading is directly proportional to its velocity. A novel algorithm called VEPSD (Velocity Estimation using the Power Spectral Density of the received signal envelope) is introduced in this paper that uses the amount of Doppler spread in the received signal envelope to estimate the velocity of a mobile user. The Doppler spread is estimated using the slope of the power spectral density (PSD) of the received signal envelope. The performance of the proposed algorithm is evaluated in both Rayleigh and Rician fading environments. The sensitivity of the estimation error to additive white Gaussian noise (AWGN), the estimation interval (effect of finite sample size), the sampling period, Rice factor (K), and the angle of arrival of the line of sight (LOS) component is analyzed and compared with the level crossing rate (LCR) and co-variance based velocity estimators. Also, it is shown that the proposed algorithm, VEPSD, can be used for velocity estimation under non-isotropic scattering and frequency selective fading and is well suited for NG wireless systems.**

Index Terms— **Resource management, Doppler spread, velocity estimation, power spectral density, fading environments.**

I. INTRODUCTION

Next Generation (NG) wireless systems are envisioned to provide users with reliable services equivalent to that of wireline communication systems. This requires intelligent techniques to eliminate the QoS degradation and forced termination that may occur when enough resources are not available to accommodate handoff requests. Information about the position and velocity of the mobile users can be used to accurately predict their trajectories, which can be used to estimate the handoff instances [3]. Then resources for handoff requests can be reserved in advance. This will eliminate handoff failure and the associated QoS degradation. Studies in [1] and [3] show that information about users' mobility pattern results in enhanced resource management and QoS support in wireless systems.

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Also, in the hierarchical cellular architecture, which is being proposed for NG wireless systems, the knowledge of the users' velocity can be used to assign slow moving users to micro/pico and fast moving users to macro cells. As a result, the handoff rate for the fast moving users can be reduced. This will increase the system capacity and reduce the number of dropped calls, and hence, will enable the network to provide an improved quality of service (QoS) [4] using its limited resource.

There exist several techniques in the literature for velocity estimation in wireless systems. In [9] a velocity estimation algorithm is proposed using the Doppler effect in vehicular noise. The algorithm proposed in [4] using the normalized auto-correlation values of the received signal is efficient in classifying the velocity into slow, medium, or fast. However, a better resolution of the velocity is not achievable. In [2] the level crossing rate (LCR) based velocity estimator is proposed. However, in the presence of AWGN, this estimator suffers from severe estimation error when the velocity is low. Wavelets are used in [12] for velocity estimation. Switching rate of diversity branches is used for the velocity estimation in [10], but it is shown in [7] that this method is sensitive to the fading scenarios. Hence, it is not practical. In [16] velocity estimation algorithms are proposed that uses pattern recognition. However, these are computationally intensive [4]. In [11] a velocity estimator based on statistical analysis of the channel power variations is proposed. In [8] the squared deviations of the received signal envelope is used for velocity estimation. Adaptive array antennas are used for the velocity estimator proposed in [6]. The first moment of the instantaneous frequency of the received signal is used in [5] for the velocity estimation. However, this study is limited to Rayleigh fading channels.

It is desirable to have an algorithm to estimate the mobile velocity to the desired level of accuracy. The level of accuracy depends on its use. For example, for assignment of users to a macro, micro, or pico cell, a coarse estimation of velocity classifying it to slow, medium or fast is sufficient. On the other hand, an accurate velocity estimation is required to predict the trajectory of the mobile users. The estimation accuracy of the algorithm should remain the same over a large velocity range i.e., for low, medium and high velocity values. It is required that the accuracy of velocity estimation to be independent of the fading types and frequency selectivity of the channel. Moreover, the algorithm should not be computationally extensive. Also, the algorithm should be able to track the change in velocity accurately, especially when the velocity is used for tracking the mobile users. To our knowledge none of the existing velocity estimation techniques satisfy all these requirements simultaneously. Hence, there is a need to find a velocity estimation technique having all these properties.

In this paper, we propose a novel algorithm called VEPSD (Velocity Estimation using Power Spectral Density of the received signal envelope) for the velocity estimation. In VEPSD, we first estimate maximum Doppler spreading frequency (f_m). Then we use this information for velocity estimation. VEPSD has the requirements of an efficient velocity estimation algorithm.

The rest of this paper is organized as follows. In Section II, we provide a detailed description of the proposed VEPSD algorithm. We select the simulation parameters and discuss the simulation results in Section III. Finally, we summarize the performance and advantages of our velocity estimation algorithm and present the conclusions in Section IV.

II. VEPSD

The maximum Doppler frequency (f_m) is related to the mobile velocity (v), speed of light in free space (c), and the carrier frequency (f_c) through

$$v = f_m(\frac{c}{f_c}). \tag{1}$$

In a 2D-isotropic scattering environment with line of sight (LOS) component (i.e., Rician fading), uniform receiver antenna gain of G, and average received power with respect to an isotropic antenna equal to A , the power spectral density (PSD) of the received signal envelope, $S(f)$, is expressed as [13]

$$S(f) = \begin{cases} \frac{AG}{\pi f_m \sqrt{1-(\frac{f-f_c}{f_m})^2}} + N_0, \\ \qquad |f-f_c| < f_m, f-f_c \neq f_s \\ \frac{AG}{\pi f_m \sqrt{1-(\frac{f-f_c}{f_m})^2}} + s^2 + N_0, \\ \qquad f = f_c + f_s \\ N_0, \\ \qquad f_m < |f-f_c| < B. \end{cases} \tag{2}$$

where N_0 is the noise PSD and $2B$ is the receiver bandwidth. $f_s = f_c + f_m \cos\theta_0$ and $s^2 = 2\sigma^2 K$ are the frequency and power of the LOS component, respectively. θ_0 and K are the angle of arrival of the LOS component and Rice factor, respectively. The plot of (2) is shown in Fig. 1. For a Rayleigh fading channel, i.e., a channel with no LOS component, $S(f)$ can be derived from (2) when $s = 0$ and its plot is similar to Fig. 1, except that there is no LOS component. We differentiate (2) to get the slope of $S(f)$ in Rician fading environment, which can be expressed as

$$\frac{dS(f)}{df} = \begin{cases} \frac{A.G(f-f_c)}{\pi f_m^3 [1-(\frac{f-f_c}{f_m})^2]^{\frac{3}{2}}}, \\ \qquad |f-f_c| < f_m, f-f_c \neq f_s \\ \frac{A.G(f-f_c)}{\pi f_m^3 [1-(\frac{f-f_c}{f_m})^2]^{\frac{3}{2}}} + \delta(f+f_s), \\ \qquad f = f_c + f_s \\ 0, \qquad f_m < |f-f_c| < f_B. \end{cases} \tag{3}$$

In (3), the slope has three maxima: at $f = f_c + f_m$, $f = f_c - f_m$, and $f = f_c + f_s$. The maximum at $f = f_c - f_m$ and $f = f_c + f_m$ are due to the maximum Doppler frequency. The maximum at $f = f_c + f_s$ is because of the LOS component. When the angle of LOS component $\theta_0 = 0$, the maximum of (3) due to f_m and f_s coincide with each other. Note that when no LOS component is present (Rayleigh fading channel) (3) has only two maxima at $f = f_c + f_m$ and $f = f_c - f_m$. Therefore, for both Rayleigh and Rician fading, the slope of PSD of the received signal envelope has maximum values at frequencies $f_c \pm f_m$. The frequency component, $f = f_c + f_m$, is always greater than or equal to $f = f_c + f_s$ and greater than $f = f_c - f_m$. We detect the maximum value of (3) which corresponds to the highest signal component to estimate f_m.

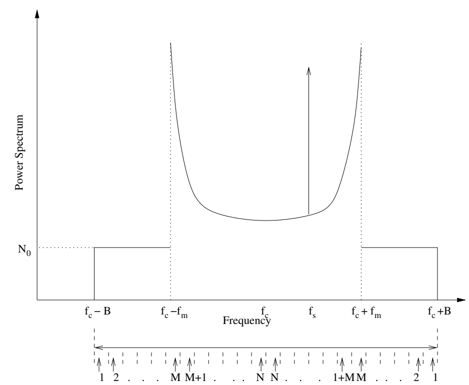

Fig. 1. PSD of received envelope in Rician fading environment in the presence of AWGN.

For practical implementation, we use discrete slope calculation. We divide the entire receiver bandwidth ($2B$) into $2N$ equally spaced intervals as shown in Fig. 1. Each interval has a mirror image about f_c. The discrete frequency value associated with the i^{th} interval is $f_c + B - (\frac{B}{N})i$. We calculate the slope as

$$S(k) = \frac{\sum_{i=1}^{k+1} P(i) - \sum_{i=1}^{k} P(i)}{2\Delta B} = \frac{P(k+1)}{2\Delta B} \tag{4}$$

where $P(i)$ is the sum of the power of i^{th} interval and its mirror image interval. $\Delta B = \frac{B}{N}$ is the width of one interval. Using (4) and Fig. 1, it is clear that, $S(i), i = 1, 2, \ldots, (M-2)$, have the same value and equal to PSD of AWGN, N_0. In a real scenario, N_0 is not flat. Hence, $S(i), i = 1, 2, \ldots, (M-2)$, are not exactly equal to each other. Their values are close to N_0 and different from each other. When noise PSD (N_0) is insignificant compared to the power in the interval containing frequency $f = f_c + f_m$, $S(M-1)$ will be dominant among all the slopes in a Rayleigh fading scenario. On the other hand in a Rician fading scenario the slopes corresponding to the intervals containing $f_c + f_m$ and $f_c + f_s$ are both dominant. But the slope corresponding to the interval containing $f_c + f_m$ is of lower order compared to the one corresponding to the interval containing $f_c + f_s$, where the order of the slope is given by 'k' in (4). When both $f_c + f_m$ and $f_c + f_s$ belong to the same interval, there is only one dominant slope in case of Rician fading scenario. We detect the lowest order dominant slope of the received signal envelope's PSD to estimate f_m. This ensures that our algorithm is independent of the fading environment.

The estimation of the lowest order dominant slope can be carried out in two ways: (1) one way is to calculate all the slopes and then detect the peak slope of lowest order and (2) the other way is to calculate $S(1)$, then $S(2)$, and so on until the first dominant slope is detected. In this approach, initially the values of the slopes ($S(1), S(2)$ etc.) are close to N_0 up to the slope corresponding to the interval containing $f_c + f_m$. The slope corresponding to interval containing $f_c + f_m$ is significantly higher than N_0. This is the lowest order dominant slope. There is no need to calculate the other slopes.

For the second approach, there is no need to calculate all the slopes and no sorting is required. Therefore, it has less computational complexity. However, it requires the knowledge about N_0. This requirement can be eliminated if the worst case SNR for the mobile system is known. If the value of N_0 corresponding to worst case SNR is $N_{0(worst)}$, then in the second approach initially the values of slopes corresponding to the intervals before the interval containing $f_c + f_m$ are less than or equal to $N_{0(worst)}$. And the slope corresponding to the interval containing $f_c + f_m$ is significantly higher than $N_{0(worst)}$. Therefore, with the knowledge of $N_{0(worst)}$ in the second approach, when a particular slope is significantly greater than $N_{0(worst)}$, we consider that as the lowest order peak slope. We refer to $N_{0(worst)}$ as slope threshold, S_{th}, in the rest part of the paper. We use the second approach because of its low computational complexity. If the lowest order peak slope corresponds to $k = k_{min}$, then

$$f_m = B - k_{min}(\Delta B) \tag{5}$$

To further reduce the computational complexity, we use a two-step approach to estimate f_m.

- First, we carry out a coarse estimation of $f_m = f_m^1$ using interval width of ΔB_{coarse} for slope calculation in (4). If we denote the index of slope corresponding to lowest order peak as k_{coarse}, f_m^1 is expressed as

$$f_m^1 = B - k_{coarse}\Delta B_{coarse} \tag{6}$$

- Then, we carry out a finer estimate of $f_m = \hat{f_m}$ using interval of ΔB for slope calculation in (4). In this step, we calculate the slope of the received signal envelope's PSD in the frequency range over $f_m^1 - x$ to $f_m^1 + x$. Our choice of $2x$ Hz over which the slope is calculated is arbitrary. Any value for x can be used as long as $2x$ exceeds $2\Delta B_{coarse}$ (which is the granularity of the previous step). If we denote the index of the peak slope, which has the lowest order as k_{finer}, then $\hat{f_m}$ is given by

$$\hat{f_m} = f_m^1 + x - k_{finer}\Delta B. \tag{7}$$

Finally, we estimate the velocity using $f_m = \hat{f_m}$ in (1). From (5), it is clear that the accuracy of velocity estimation depends on the interval width, $\Delta B = \frac{B}{N}$. As NG wireless systems are expected to work at higher carrier frequencies, the maximum Doppler spread for a particular velocity will increase. Let v_{curr} and v_{NG} are the velocities corresponding to the maximum Doppler frequency of ΔB in the current and NG wireless systems respectively. Then, $v_{NG} = v_{curr} * (\frac{f_{c(curr)}}{f_{c(NG)}})$, where $f_{c(NG)}$, and $f_{c(curr)}$ are the carrier frequencies in the NG and the current wireless systems respectively. The NG wireless systems are expected to operate at carrier frequencies around 5 GHz. The velocity corresponding to the maximum Doppler spread of 5 Hz is 1.08 km/h. Therefore, the accuracy in the velocity estimation will improve to 1.08 km/h, as opposed to 2.7 km/h in the current system ($f_c = 2$ GHz), for $\Delta B = 5$ Hz. Note that the improvement in estimation accuracy is independent of ΔB. Another advantage of our algorithm is its scalability. The algorithm can be used to estimate the velocity up to the desired level of accuracy. This is possible through proper selection of the number of intervals (N) for slope calculation. For example, to determine if the velocity of the mobile is slow, medium or fast, we just need three intervals. On the other hand, using more number of intervals an accurate estimation of the velocity can be achieved.

A. The Velocity Estimation in Non-Isotropic Scattering Environments

So far we discussed the algorithm for isotropic scattering environments. Non-isotropic scattering is usually modeled using von Mises/Tikhonov distribution [14], where the probability distribution of θ is given by

$$p(\theta) = \frac{1}{2\pi I_o(\kappa)} e^{\kappa\cos(\theta-\alpha)}, \theta \in (-\pi, \pi] \tag{8}$$

where $I_o(\kappa)$ is 0^{th} order modified Bessel function of the first kind, κ is the beam width, and α is the angle that the average scattering direction makes with the mobile direction. The PSD of the received envelope has maximum values at frequencies $f_c \pm f_m$. Hence, f_m can be detected using our VEPSD algorithm. This ensures that the VEPSD algorithm is applicable to both isotropic and non-isotropic scattering environments.

B. The Velocity Estimation in Frequency Selective Environments

All our previous discussion about the velocity estimation algorithm is based on the fact that the mobile channel experiences frequency non-selective fading. This is not true for wide band mobile systems where the channel is often frequency selective. Nevertheless, we have the access to the flat fading received envelope even when the fading is frequency selective [15]. Therefore, the proposed VEPSD algorithm can also be used in frequency selective fading. For example, in case of multi-carrier systems the channel across any one of the sub-carrier experiences frequency non-selective fading, hence the received signal envelope for any of the sub-carriers can be used for the velocity estimation algorithm. Also, the flat fading received envelope can be obtained from RAKE receiver in case of CDMA systems [15].

III. PERFORMANCE EVALUATION OF THE ALGORITHM

We carried out the performance evaluation of the VEPSD algorithm through simulation using the fading model proposed by Jakes [13]. We selected the receiver bandwidth B such that it is just greater than the maximum Doppler spread for the highest vehicular velocity to minimize the effect of noise on estimation [2]. We consider $B = 325$ Hz, which allows velocity up to 175 Km/h at $f_c = 2$ GHz. We use $f_c = 2$ GHz, as this frequency band is widely used for cellular systems. We consider $\Delta B = 5$Hz that can estimate velocity to an accuracy of 2.7 km/h. We use $\Delta B_{coarse} = 27$ Hz. To determine the value of slope threshold, S_{th}, we assume the worst case SNR to be 15 dB. This assumption is realistic as the typical SNR in cellular systems is of the order of 20 dB [8]. The threshold value is determined in such a way that, $S_{th} >> N_0$. This ensures that slight variation in N_0 is not identified as a dominant slope. Through simulations, the value of S_{th} for coarse estimation (6) is found to be 20 and that for finer estimation (7) is 4.5.

A. Simulation Results for Rayleigh Fading

We start with the investigation of the effect of estimation interval (T_{est}), AWGN and sampling period on the estimation error. Then we investigate the estimation accuracy for various ranges of velocity and analyze the response of the algorithm to changes in the velocity.

1) Effect of Estimation Interval: The estimation interval (T_{est}) corresponds to the time interval over which the received signal envelope samples are collected and used for the velocity estimation. Hence, $T_{est} = N{*}\tau$, where N is the number of samples used for estimation and τ is the sampling period. We vary T_{est} by keeping the sampling period constant at $\tau = 1$ ms and varying the number of samples used. The standard deviations of the estimated velocity for different estimators are shown in Figure 2. The randomness in velocity estimation decreases as the estimation interval (T_{est}) increases as shown in Fig. 2. Because the envelope samples belong to a random process, a longer interval gives a smoother result. This is true for all the three estimators. The standard deviation of estimation saturates at $T_{est} > 1$s. The standard deviation for the VEPSD algorithm is least for all values of estimation interval as shown in Fig. 2. For all our subsequent experiments, we used $T_{est} = 1$ s as this gives a very good estimate of the velocity for all the three algorithms as observed from Fig. 2.

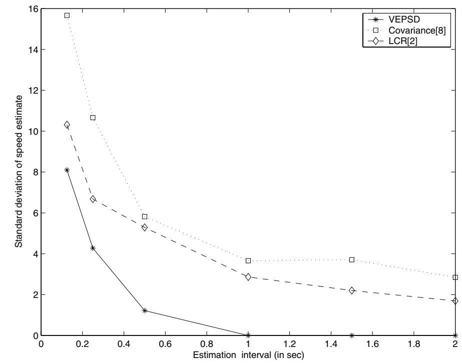

Fig. 2. Standard deviation of estimated velocity vs. estimation interval in Rayleigh fading environment: $v = 40$ km/h, $\tau = 1$ ms and SNR=20 dB.

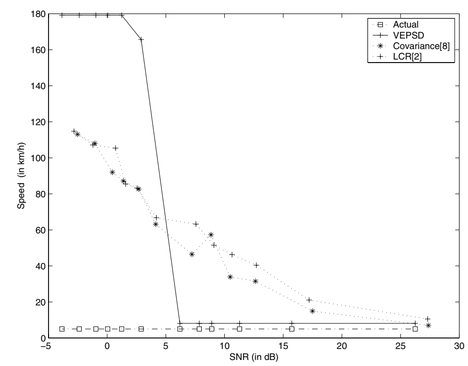

Fig. 3. Estimated velocity vs. SNR in Rayleigh fading environment for $\tau = 1$ ms and $T_{est} = 1$ s, and $v = 5$ km/h.

2) Effect of AWGN: Figure 3 and 4 show the performance of the velocity estimation algorithms vs SNR for velocity values of 5 km/h and 40 km/h, respectively. For VEPSD estimator the performance is degraded when the SNR is below 7 dB in Fig. 3 and 9 dB in Fig. 4. This is because below these values, the relation $S_{th} >> N_0$ does not hold. Hence, the clear existence of the dominant value of the slope corresponding to frequency f_m is lost. From Figures 3 and 4 it is clear that at very low SNR, the VEPSD algorithm always estimates the velocity to be 179 km/h. This is because for very low SNR, $N_0 > S_{th}$. Therefore, the VEPSD algorithm detects interval (1) as the interval corresponding to peak slope, both in coarse and fine estimation steps. Now, using (6) and (7), f_m is estimated as 331 Hz and the corresponding velocity is 179 km/h. Figures 3 and 4 show that the error in velocity estimation increases as the SNR decreases for both co-variance [8] and LCR [2] based methods. Also, estimation error is severe for lower velocity compared to that for higher velocity for both LCR [2] and co-variance [8]. Interestingly, the estimation error for VEPSD is independent of SNR when SNR is more than 10 dB for both low and high velocity values.

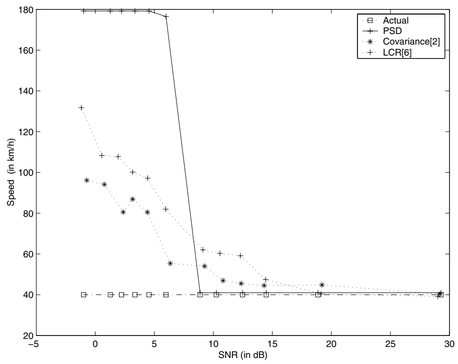

Fig. 4. Estimated velocity vs. SNR in Rayleigh fading environment for $\tau = 1$ ms and $T_{est} = 1$ s, and $v = 40$ km/h.

3) Effect of Sampling Period: For our simulations, we assume a maximum velocity of 120 km/h, which corresponds to maximum Doppler spread of 190 Hz. From Nyquist criteria, the minimum required sampling frequency is 380 Hz to avoid aliasing. We used minimum sampling frequency of 500 Hz, which corresponds to sampling period of 2 ms. The effect of sampling period on the velocity estimation accuracy is shown in Figures 5, 6, and 7. They show that for sampling period less than or equal to 2 ms, the estimation accuracy for the VEPSD based algorithm is independent of the sampling period after a particular SNR value, e.g., 8 dB for $\tau = 2$ ms, 13 dB for $\tau = 0.5$ ms, and 18 dB for $\tau = 0.125$ ms. On the other hand, the estimation accuracy for both LCR [2] and co-variance [8] based estimators degrades vs. SNR as the sampling period is decreased.

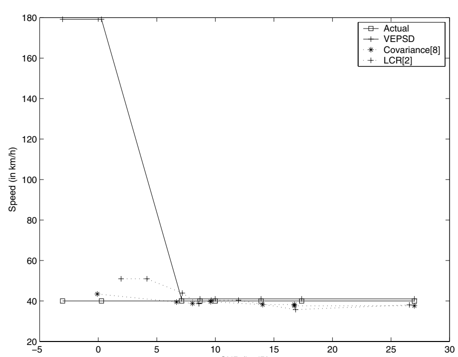

Fig. 5. Estimated velocity vs. SNR in Rayleigh fading environment: $v = 40$ km/h, and $T_{est} = 1$ s, and $\tau = 2$ ms.

4) Velocity tracking: Figure 8 shows that the tracking performance of all the three algorithms are comparable when the mobile is either accelerating or decelerating. When the mobile stays at a constant velocity, VEPSD has better accuracy of estimation than those of LCR [2] and co-variance [8] based estimators. This is because of the randomness of the received envelope, which varies the LCR count and also the variance from time to time. The VEPSD algorithm performs better in this case because even for the randomly varying received envelope, the maximum Doppler frequency, which the algorithm uses, remains constant during each observation interval.

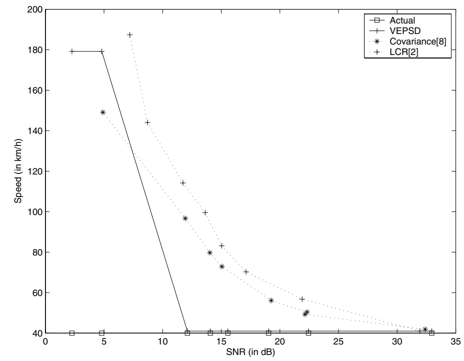

Fig. 6. Estimated velocity vs. SNR in Rayleigh fading environment: $v = 40$ km/h, and $T_{est} = 1$ s, and $\tau = 0.5$ ms.

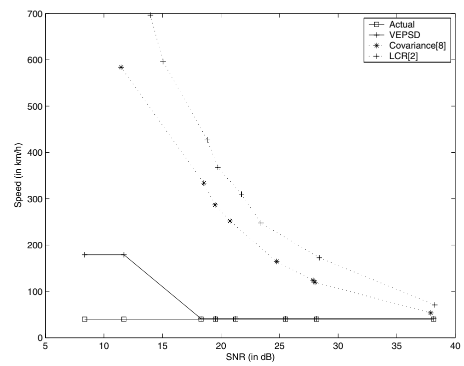

Fig. 7. Estimated velocity vs. SNR in Rayleigh fading environment: $v = 40$ km/h, $T_{est} = 1$ s, and $\tau = 0.125$ ms.

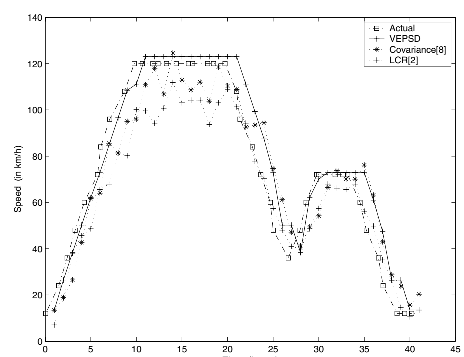

Fig. 8. Velocity tracking in Rayleigh fading environment:$\tau = 1$ ms, $T_{est} = 1$ s, SNR=20 dB.

B. Simulation Results for Rician Fading

Figures 9 and 10, show that for VEPSD algorithm the velocity estimation accuracy is independent of θ_0 and Rice factor (K). This is in contrast to the co-variance [8] based algorithm, where the accuracy of velocity estimation depend on K and θ_0 as shown in Fig. 10. The LCR [2] based estimator is robust to Rice factor (K), when the level is chosen as the rms value of the received envelope samples. This also is clear from Fig. 9, where the velocity estimation based on LCR [2] depends only on the angle of arrival of the LOS component (θ_0) and is independent of the Rice factor. The robustness of VEPSD algorithm to K can be explained as follows. As K increases, the power of the LOS component increases and that of the scattered components decreases. But still the nature of the PSD plot and hence its slope remains unchanged. Just that the value of slope decreases. For SNR value more than 15dB, this value of slope is much more than S_{th}. So the VEPSD algorithm still detects the peak corresponding to f_m. The value of θ_0 determines the position of the LOS frequency component ($f_c \pm f_s$) with respect to $f_c + f_m$. But our VEPSD algorithm always discards the peak value of slope at $f_c \pm f_s$, as discussed in Sec. II. Hence, it is insensitive to θ_0.

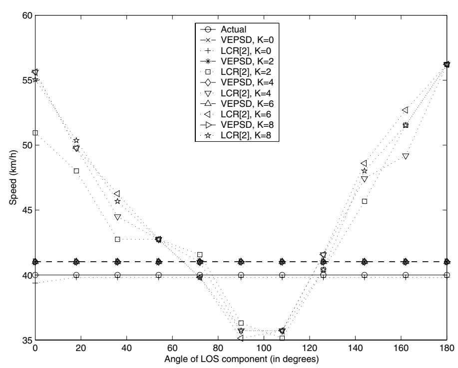

Fig. 9. Comparison of VEPSD estimator for $v = 40$ km/h, $\tau = 1$ ms, $T_{est} = 1$ s, SNR=20 dB with LCR based estimator.

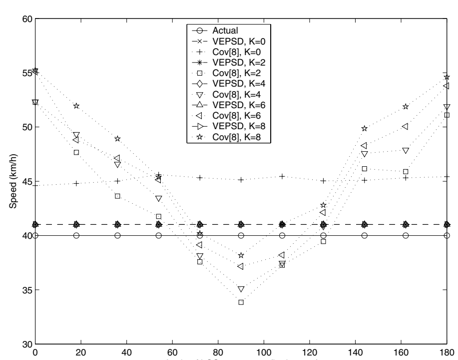

Fig. 10. Comparison of VEPSD estimator for $v = 40$ km/h, $\tau = 1$ ms, $T_{est} = 1$ s, SNR=20 dB with co-variance based estimator.

IV. Concluding Remarks

In this paper, we presented VEPSD, a novel velocity estimation algorithm. We carried out a detailed performance analysis of the proposed algorithm and also compared our algorithm with two others namely, LCR and covariance based velocity estimation. The results show that our algorithm works very well in both Rayleigh and Rician fading environments. We also showed that it can be used in other types of non-isotropic scattering and frequency selective fading environments. The VEPSD algorithm is robust to both Rice factor and angle of LOS component. This is a key advantage compared to LCR and co-variance based velocity estimators. We investigated the effect of AWGN and estimation interval, on the accuracy of velocity estimation. For all these cases our algorithm works significantly better in the SNR range typical of cellular systems. In addition, the tracking performance of the VEPSD estimator is comparable to other estimators. The estimation accuracy of VEPSD improves for NG wireless systems operating at higher frequencies. Our velocity estimation algorithm can be used to estimate the velocity up to the desired level of accuracy. By using the accurate velocity estimation of VEPSD, the trajectories of the mobile users can be estimated. The trajectory information can be used to achieve enhanced resource management and QoS support in the wireless communication systems.

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